Development and testing of a multi-transducer system for measuring height of condensed water in steam pipes with steady-state and turbulent flow conditions

Shyh-Shiuh Lih, Hyeong Jae Lee, Yoseph Bar-Cohen, Mircea Badescu, William Cervantes, and Alan Simonini
Jet Propulsion Laboratory/California Institute of Technology, MS 67-119, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, 626-390-6075, lih@jpl.nasa.gov, Web: http://ndeaa.jpl.nasa.gov.

ABSTRACT

One of the critical requirements for ensuring the safety of a steam pipe is to monitor the condensed water level under operation. For this objective, the authors initially developed methods and obtained preliminary test results based on the use of ultrasonic pulse-echo transducers and enhanced signal-processing tool; however, the methodology needed further development in order to obtain measurements in turbulent dynamic flow conditions. To improve the reliability of measurements taken in turbulent flow conditions, an experimental system was developed using multiple transducers driven by a multiplexer, and a data acquisition module capable of operating in any flow conditions. The system consists of a simulation testbed, which allows testing the performance over a range of flow rates and water levels and to observe flow conditions and patterns, as well as measure actual water level, flow velocities, wave conditions, etc. In this paper, we present the development details that include description of the testbed for simulating the flow of condensed water, the multiple transducers arrangement, the signal processing method, and the test results of both steady state and turbulent flow.

Keywords: NDE, NDT, Health monitoring of steam pipes, ultrasonic pulse-echo

Introduction

Steam pipes are used in various major metropolitan areas across the world. Healthy monitoring of these pipes while in operation is critical to public safety. One of the critical requirements of a steam pipe is to monitor the condensed water level inside the pipe under operation. To fulfill this requirement, the authors developed and reported a series of innovative technologies and testing results based on the use of ultrasonic pulse-echo and enhanced signal-processing methods [Bar-Cohen et al., 2010 and 2011; Lih et al., 2013 and 2016]. In these publications, the developed healthy monitoring system is reported to operate at temperatures as high as 250ºC using enhanced signal processing techniques [Lih et al., 2013 and Lih et al., 2015] for a single transducer system. The objective of the developed system is to provide early alert that will prevent potential failure of the pipe. The results obtained in the lab and the field demonstrated the feasibility and efficiency of the system. The received signals are affected by a strong ringing because of reflection from steel pipe interfaces and the local rough outside surface of the pipe, and attenuation causes loss of the reflected amplitude. The amplitude is significantly affected in service by the dynamic environments that are involved, including vibration of the support structures, ripples of the water surface induced by the fast-blown steam, temperature variation, presence of bubbles, potential water hammer effect, etc. The water hammer and other severe water flow conditions may lead to serious consequences including damaged vents, traps, regulators and piping.

Under turbulent flow conditions, it is difficult to obtain accurate measurement of the water height inside the pipe with a single transducer system and therefore we investigated the use of multiple probes (Error! Reference source not found.**)**. The probes were driven by a multiplexer and data acquisition module and the tests were done at steady-state and turbulent flow conditions. To stimulate turbulent conditions, a testbed was designed and constructed that produced a range of flow rates and water levels. To expand signal reception angles, additional probes were needed around the pipe to act as both transmitters and receivers.

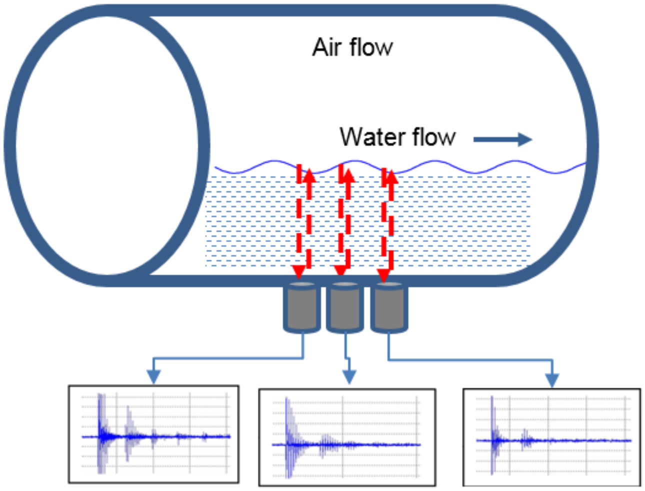

Figure 1. Pulse-echo test method with multiple probes mounted to the steam pipe.

Experimental Setup

To test and demonstrate the performance of the measurement method, we designed and produced a testbed that simulates the flow of condensed water. In addition, in order to maximize the capability and reliability of the ultrasonic pulse/echo method, efforts were focused on making required modifications to the existing signal processing algorithms and test system.

Attention has been given to the possibility that the water surface may have various shapes including wavy, and circumferential around the internal surface of the pipe. The use of multiple probes has been investigated to address the effect of water surface curvature on wave reflection to the transmitter/receiver probe. There has been a concern that this effect may potentially prevent detection of reflected signals that are critical to pulse/echo measurement accuracy. A multiplexer has been incorporated into the ultrasonic system that controls the sequence of activating the multiple probes, thus, optimizing the reliability of the measurements. Efforts were also made to maximize the sensitivity of the ultrasonic probes and the resolution of the measurements by examining various resonance frequencies with large bandwidth.

To test the effect of the water's wavy flow and surface geometry, a testbed was developed to produce water surface variations using an air blower and thus simulating various dynamic conditions of flow in the pipe. The testbed consists of three main sections: pipe assembly, airflow system, and water return system. The pipe assembly contains 4 sections of Plexiglas piping and 1 section of steel test tube totaling 15 ft. long. The Plexiglas section provided airflow stabilization, while the steel section mimicked piping commonly used for steam applications. Gaskets were mounted between flanges that connect the different segments of pipe. Along with the gaskets, height control panels were incorporated between the first and last connections, which not only controlled the water height but also kept the flowing water away from the fan and allowed better control of the water return into a water-draining tank. The steel pipe section was designed with a Plexiglas window to allow viewing of the water's formation against the pipe at any given time.

A fan was connected to the front end of the pipe and its speed controlled the flow rate through the pipe system. An anemometer was placed within the pipe system to measure the exact air speed through the pipe. The air exhaust system vented flowing air out of the back end of the pipe, allowing water to flow freely into a drainage tank.

The water return system was designed with an inline filter inside the tank to separate any debris that might cause the pump to fail. A variable pump was included in order to regulate how much water is allowed to flow into the system. The design also included return hoses connected to the pump and then to the tank and back into the pipe as indicated by the arrows in **Figure 2 (left)**. Before the water was pumped into the main pipe section, a flowmeter was used to determine the flowrate of the water entering the system Error! Reference source not found. **(right)**.

Multiple ultrasonic probes and their mounting fixture

We use multiple probes in the system to provide multiple "opinions" regarding potentially suspicious measurements. These may result from practical causes like degradation of the pipe-probe interface or internal pipe corrosion. Multiple probes also allows for dealing with two dimensional cross-sectional profile of condensed water. **Figure 2** shows the experimental setup that was used for analyzing the water height inside the pipe using multiple ultrasonic sensors. For controlling the signals and their analysis using data acquisition and processing software, the monitoring system included a multiplexer pulser/receiver, a preamplifier, high temperature probes [Bar-Cohen, 2014], and a microprocessor. To simplify mounting probes to the pipe, we used high temperature, high pull force magnets instead of the strapping mechanism used in a previous field test.

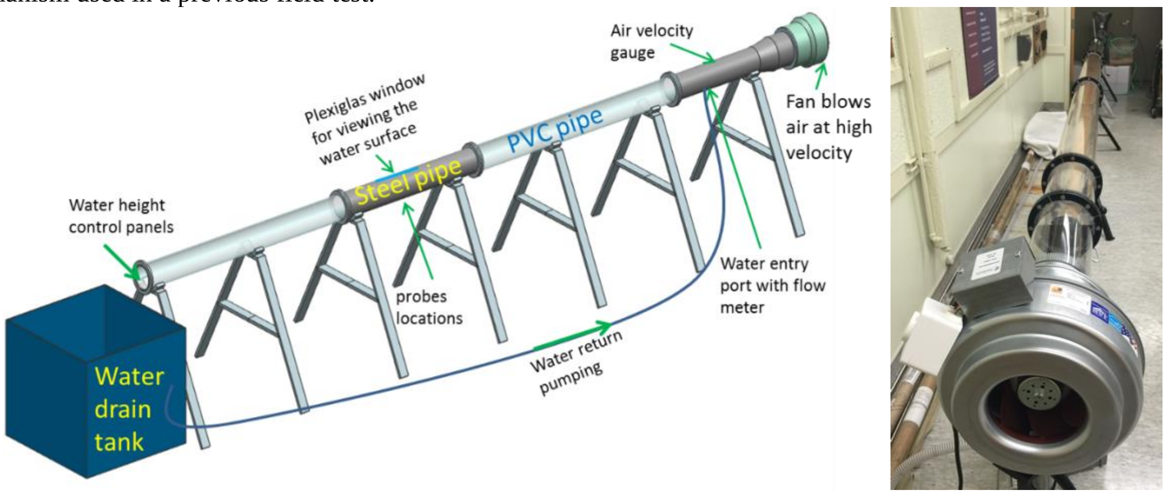

Figure 2: The experimental setup of the water flow system with a fan attached at the end of the pipe.

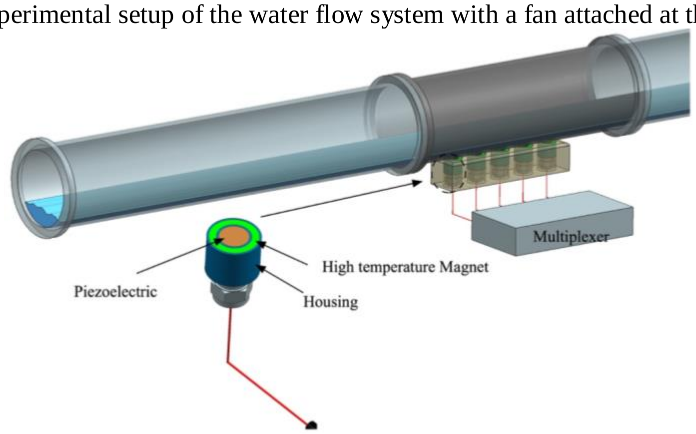

Figure 2: Initial experimental set for the water height measurement.

An eight channel multiplexer was used in the experiments. It consisted of a combination of a tone burst pulser/receiver and an analog-to-digital converter - both of which are located in a single device equipped with a universal serial bus. The device can transmit pulses from any channel and receive the reflected signal via any channel. It is capable of processing data at high speeds for real-time detection and data compression, suitable for the analyses of multiple signals.

To support the various experiments, we designed and fabricated the probe-mounting fixture as shown in **Figure 4**. In this fixture, spacing is provided between the probes. In addition, the fixture included two Socket Head screws to adjust its angle relative to the pipe. The screws allowed for stabilization of the fixture against the curved surface of the pipe and alignment in the position that gave the strongest received signal reflections. With this combination of probes and new fixture design, we were able to obtain consistent results throughout the tests.

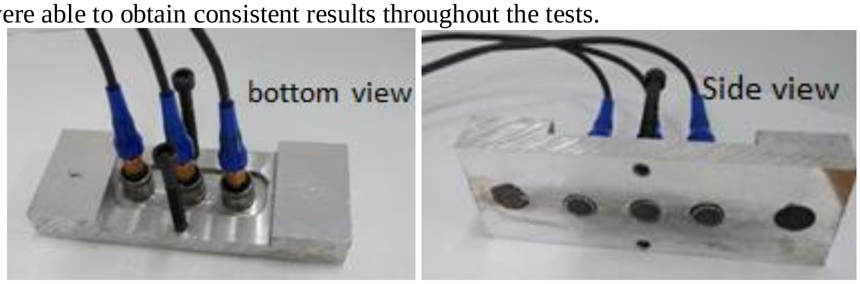

Figure 4: Adjustable fixture for easy positioning to receive strong and consistent reflection signal amplitudes.

The Signal Processing

A systematic study of the signal processing methods for the health monitoring of the water height in a steam pipe was presented in [Lih et al, 2013 and 2015]. Enhanced implementation of the signal processing procedures for a dynamic environment with multiple probes based on correlation and Hilbert transform methods can be found in [Lih et al, 2016] and are summarized as follows.

Correlation Methods

Auto-correction is one of the most widely used signal processing methods to find repeated patterns or time-of-arrival in the presence of noise. The autocorrelation function can be defined as follows:

$$R_{xx}(\tau) = \frac{1}{T}\int_0^T x(t)x(t+\tau)dt \qquad (1)$$

$$R_{X_iY_j}(\tau_j) = \frac{1}{T}\int_0^T X_i(t)Y_j(t+\tau_j)dt \qquad (2)$$

where T is the total sampling time and τ is the time separation variable. The time-of-flight (TOF) is then determined using a predetermined search window for the second maximum auto-correlation group from the calculated value of the auto-correlation. A transducer array is assumed to perform pulse-echo and pitch-catch to monitor the fluctuation of the water height due to disturbance, water flow, and other anomaly conditions via switching the input from the transmitters array $X_i(t)$. The received signals $Y_{ij}(t)$ are then correlated with the input signals to obtained the cross correlation functions R_{XY} as shown in equation (2).

Hilbert Transform and Other Methods

Discussions of alternative methods such as the Hilbert envelope and others can be found in authors' previous publications in the reference section. Using the developed signal processing tool for determining the height in real-time, the capability to handle surface and bulk interferences was tested.

Verification and validation of the test system

Multiple tests were conducted using the testbed in various dynamic conditions including increasing and decreasing water height. This was done by controlling the airflow within the pump and turning the water pump on or off, as follows:

Increasing water height when turning the water pump on

This test was followed with turning the pump off and blowing air until the water was drained. Upon activation of the water pump, the water height increased as shown in the first section of the graph in Error! Reference source not found.**5**. The graph is smooth showing that the flow rate is stable and the measured height data increased with minimal fluctuation. Once the air blower was turned on, dynamic conditions were created and the data became noisier due to the fluctuations in water height. In addition, the water height slowly decreased due to draining. This test, shown in **Figure 5,** was done after filling the pipe up to the level of the dams and letting it drain. The height can be seen dropping and the data is quite smooth.

Examples of steady state and turbulent flow conditions in the Plexiglas tube region

Two representative of experiments were conducted to verify the feasibility of the developed system as shown in **Figure 6**, which are the snap shot of a) a transitional steady state flow (left), and b) a fully developed turbulent flow (right). The Channel Reynolds number $\mathrm{Re}_{Channel}$ is used in the partially filled pipe to gauge the turbulence.

$$\mathrm{Re}_{Channel} = \frac{\rho V R_{hydrolic}}{\mu} \qquad (3)$$

where $R_{hydraulic}$ is the hydraulic radius defined by the cross sectional area of flow divided by the wetted perimeter, V is the flow speed, μ is the dynamic viscosity of water, and ρ is the density of water. Estimating this Reynold's number allowed for comparison of turbulence between tests with different flow conditions. Alternative definitions of turbulence may vary among other references.

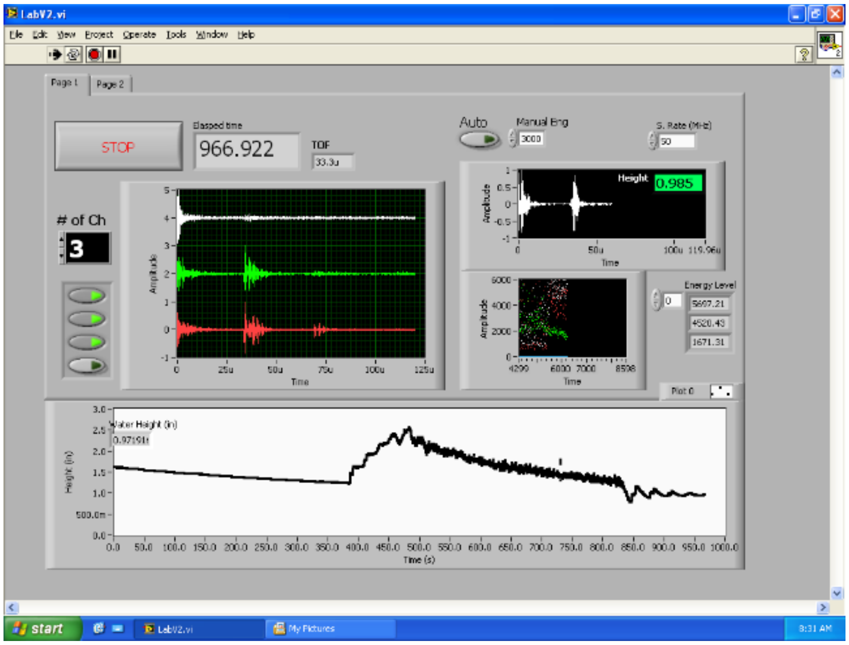

Figure 5: Test with increasing water height after turning the water pump on and with the water height decreasing at first to show a clean signal.

The first example of the testing was conducted with a one-degree inclination of the pipe, where the water pump was turned on before the fan, as shown in the left of **Figure 6,** to verify system performance. The three transducers were placed under the pipe with small gaps. The developed multiple data acquisition system was used to receive the signals and process the data to find the time of flight and determine the height in real time. The recorded raw data for channels 1 to 3, and the combined data are shown in **Figure 7**. It can be seen that all three channels consistently recorded the water level with excellent correlation. Few outliers were observed, which can be removed by the filter and moving average algorithm. The observed water level started at around 1.1 inch and gradually ramped up to 2 inch. It demonstrated the capability of the developed system to determine the water height in a highly turbulent water flow condition.

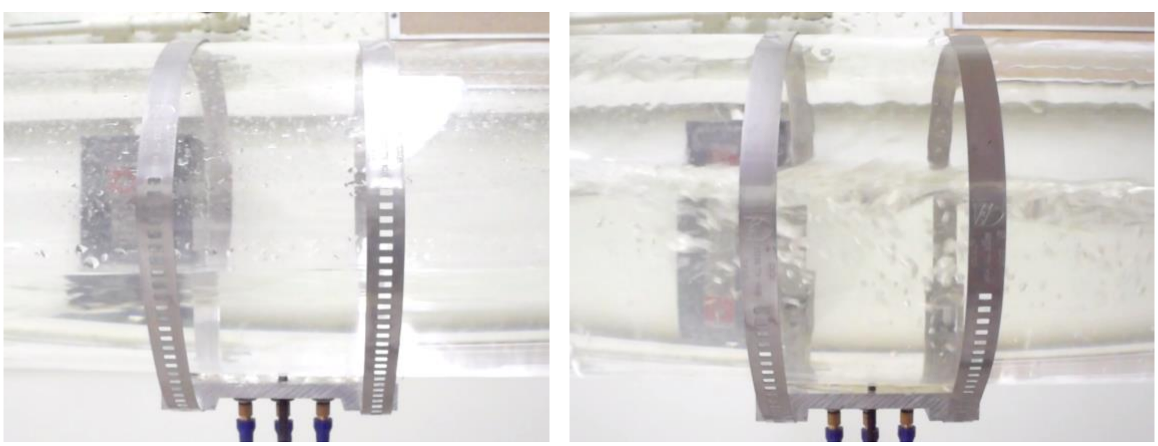

Figure 6: The snap shot of the test examples: the steady state flow (left) and the turbulent flow (right).

The second example is to verify the accuracy of the system for the turbulent flow, as shown in the right of Figure 6. Airflow is introduced by adjusting the fan speed up gradually in three stages to generate turbulent fluctuation of the water level. The recorded raw data with channels 1~3 and the combined data for the turbulent flow are shown in **Figure 8** similar to **Figure 7**. In order to investigate the turbulent fluctuations, we moved the probes location near the air-blower and tested it again. For this condition, we observed a series of turbulent fluctuations with a sudden water height change as shown in **Figure** 8. Water level is at 2 in with small oscillation and begins to show the oscillation from 45 sec between 2~3 inches. The flow is a transitional steady state flow with relative low Reynold's number compared to the turbulent flow in the test example below.

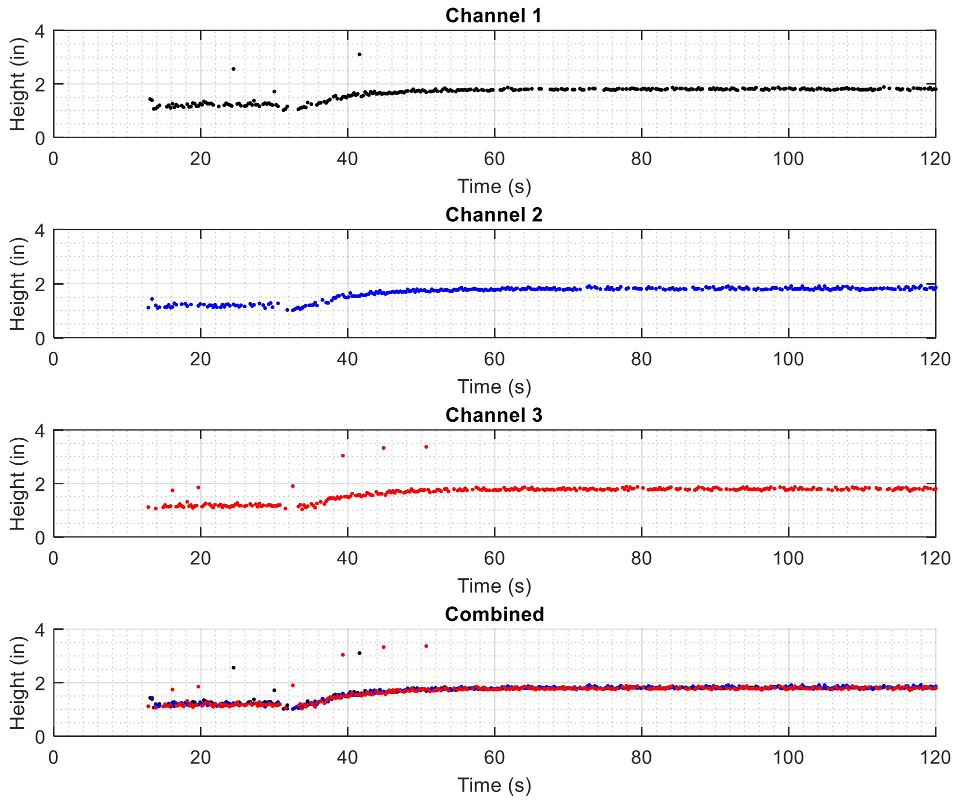

Figure 7: Measured height of water in each channel (top three) and the combination of all channels in a steady state flow.

Investigating the recorded data as show in **Figure 8** at the interval 45~110 sec, we found fewer data points were recorded when the water level was rising due to the incoming tide wave, and more data were recorded when the water level was retreating as shown in the snapshot of the wave profile within that time frame as shown **Figure 9**. The flow is highly turbulent with the observed instantaneous Reynold's number higher than 10^6. Combined testing data for the turbulent flow, as shown in **Figure 8,** from channels 1 to 3 are further resampled and filtered with a moving average algorithm as shown in figure 10. It can be seen from the figure that two group-wave pattern of envelopes were observed with a frequency of 0.36Hz between 45 and 110 sec. The fluctuation frequency and patterns of the water level information will be used for the pattern recognition of water flow and level fluctuations for the field operation.

Conclusion

A newly developed multiple probes with multiplexers system and test results are presented in this paper. The system allows for testing the water height inside steam pipes with turbulent water surface conditions. A testbed, for simulating the flow of condensed water, has been constructed and it included multiple transducers arrangement. A signal processing system that is controlled by a graphical user interface has been developed to determine the height at steady and turbulent flow conditions. The experiments demonstrated the capability of the developed systems to monitor water height information in severe disturbances and irregular water-wave flow even in inclined pipes having a positive or negative slope angle.

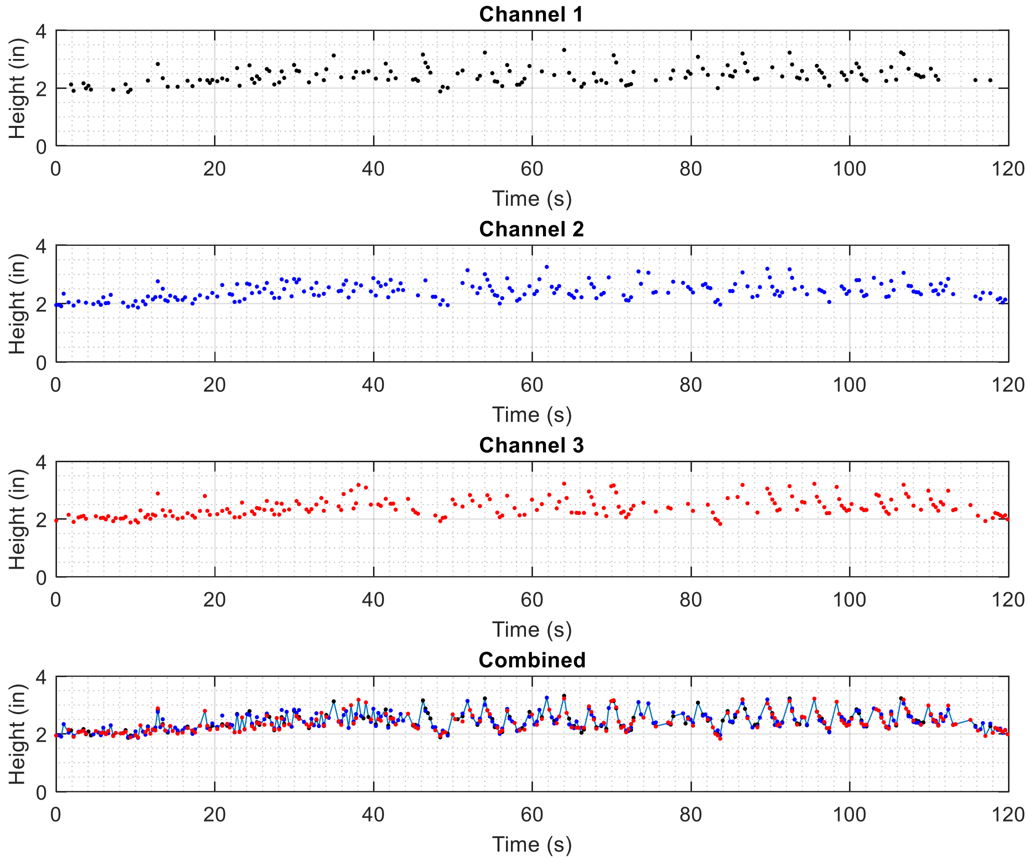

Figure 8: Measured height of water in each channel (top three) and the combination of all channels in a turbulent flow.

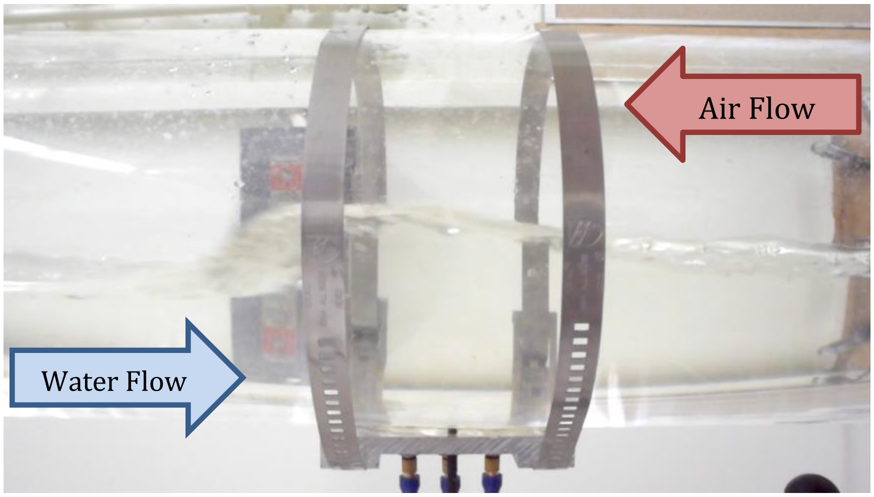

Figure 9: Snapshot of the turbulent flow with air blowing on the surface.

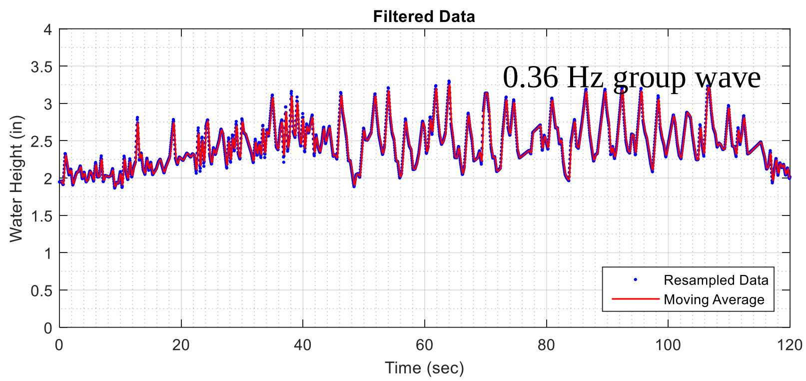

Figure 10. Refined measured and filtered water height for the turbulent flow condition.

Acknowledgment

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics Space Administration (NASA) supported by Consolidated Edison Company of New York, Inc. The authors would like to thank Josephine Aromando and Dowlatram Somrah, of the company, for their support of this task and for the inputs, comments and helpful suggestions regarding the health monitoring of the height of condensed water in steam pipes.

Reference

[1] Bar-Cohen, Y., S.-S. Lih, M. Badescu, X. Bao, S. Sherrit, S. Widholm and J. Blosiu, “In-service monitoring of steam pipe systems at high temperatures,” Proc. SPIE 7650 (2010).

[2] Bar-Cohen, Y., S-S. Lih, M., Badescu, X. Bao, S. Sherrit, S. Widholm, P. Ostlund, and J. Blosiu, “High temperature monitoring the height of condensed water in steam pipes,” Proc. SPIE 7984 (2011).

[3] Bar-Cohen Y. (Ed.), High Temperature Materials and Mechanisms, ISBN 13: 9781466566453, ISBN 10: 1466566450, CRC Press, Taylor & Francis Group, Boca Raton, Florida (2014).

[4] Lee H. J., Y. Bar-Cohen. S.-S. Lih, M. Badescu, X. Bao, S. Sherrit, N. Takano, P. N. Ostlund, and P. Blosiu, “High temperatures health monitoring of the condensed water height in steam pipe systems”, Proc. SPIE 8695 (2013).

[5] Lih S.-S., Y. Bar-Cohen, H. J. Lee, N. Takano and X. Bao, "Advanced signal processing for high temperatures health monitoring of condensed water height in steam pipes," Proc. SPIE 8695 (2013).

[6] Lee H. J., Y. Bar-Cohen. S.-S. Lih, M. Badescu, X. Bao, D. Arsham, N. Takano, and P. Blosiu, “Wireless monitoring of the height of condensed water in steam Pipes”, Proc. SPIE 9063 (2014).

[7] Lih S.-S., Y. Bar-Cohen, H. J. Lee, “Signal processing for determining water height in steam pipes with dynamic surface conditions,” Proc. SPIE 9438 (2015).

[8] Lih S.-S., H. J. Lee, Y. Bar-Cohen, “In-situ measurement of the height of condensed water in steam pipes with dynamic flow,” Proc. SPIE 9805 (2016).